Physics Prospects at the Hadron Colliders*

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Abstract

I start with a brief introduction to the elementary particles and their interactions, Higgs mechanism and supersymmetry. The major physics objectives of the Tevatron and LHC colliders are identified. The status and prospects of the top quark, charged Higgs boson and superparticle searches are discussed in detail, while those of the neutral Higgs boson(s) are covered in a parallel talk by R.J.N. Phillips at this workshop.

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The hadron colliders are best suited to explore a new domain of energy for a wide variety of new physics signals because of their higher energy reach and greater versatility. With the loss of SSC, one looks forward to the Tevatron upgrade and especially the large hadron collider (LHC) to survey the energy range of $100-1000$ GeV. I plan to give an overview of the main physics issues to be probed by these colliders. To put them in perspective, let me briefly recall our current understanding of the elementary particles and their interactions.

Basic Constituents of Matter and Their Interactions – As per the standard model, the basic constituents of matter are the 3 pairs of leptons and quarks shown below. Each pair represents 2 charge states differing by 1 unit – charge 0, -1 for the leptons and 2/3, -1/3 for the quarks – which is relevant for their weak interaction. Apart from this electric charge of course the quarks possess the so-called colour charge, which is relevant for their strong interaction.

Table 1. Basic Constituents of Matter

leptons	charge	quarks	charge
$\nu_e\ \nu_\mu\ \nu_\tau$	0	u c t	2/3
e μ τ	-1	d s b	-1/3

Almost half of these elementary particles have been observed during the last two decades, thanks to the advent of the colliders. The discovery of the τ lepton and the charm quark and study of their detailed properties were the highlights of the SPEAR (e^+e^-) collider. Although the bottom quark was first discovered in a fixed target hadron machine (the Fermilab SPS), its detailed study could be made only at the DORIS and CESR (e^+e^-) colliders. The first experimental evidence (though still indirect) of ν_τ has come from the observation of $W \rightarrow \tau\ \nu_\tau$ events at the CERN $\bar{p}p$ collider. These are the (in)famous monojet plus missing-p_T events of the UA1 experiment which were originally thought to signal supersymmetric particle production. As regards the top quark – the last and the most massive member of the above table – the CDF experiment has recently reported a tentative signal in the mass range

of ~ 175 GeV [1,2] from the Tevatron $\bar{p}p$ collider.[1] One expects a more definitive signal to emerge from the ongoing CDF and $D\oslash$ experiments at the Tevatron collider. For there is sufficient indirect evidence for the existence of top quark in the above mass range, as we shall see below.

Next consider the interactions between these elementary particles. Apart from gravitation, which is too weak to be of interest to particle physics phenomenology, there are 3 basic interactions – strong, electromagnetic and weak. They are all gauge interactions, mediated by vector particles. The strong interaction (QCD) is mediated by the exchange of massless vector gluons with couplings proportional to the colour charge C (Fig. 1a). This is analogous to the electromagnetic interaction (QED), mediated by the massless vector photon with couplings proportional to the electric charge e (Fig. 1b). The gluon was detected at the PETRA (e^+e^-) collider via the three-jet events coming from gluon radiation [3]

$$e^+e^- \rightarrow q\bar{q}g .$$

Unlike the photons which possess no electric charge the gluons possess colour charge and can therefore interact among themselves. The gluon self interaction, the most distinctive feature of strong interaction, has been observed at the CERN $\bar{p}p$ collider, via the two-jet events coming from [3]

$$gg \xrightarrow{g} gg.$$

The weak interactions are mediated by the massive charged and neutral vector bosons $W^{\pm}$ and Z°. The charged W boson couples to each of the above pairs of leptons and quarks with the same universal coupling (Fig. 1c), while the Z boson couplings are given by the standard $SU(2) \times U(1)$ electro-weak model of Glashow, Weinberg and Salam in terms of the mixing angle θ_W. It also relates the weak and electromagnetic couplings

$$\alpha_W = \alpha / \sin^2 \theta_W , \tag{1}$$

where $\sin^2 \theta_W$ is known from the neutrino scattering (and more recently the LEP data) [1], i.e.

$$\sin^2 \theta_W \simeq .23 . \tag{2}$$

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[1]These top quark candidate events of the CDF experiment were reported [2] after the WHEPP-3; but a brief discussion of these events shall be included for the sake of completeness.

Thus the W mass is predicted by estimating the Fermi coupling from μ decay (Fig. 1c); i.e

$$G_F = \frac{\pi}{\sqrt{2}} \frac{\alpha_W}{M_W^2} = \frac{\pi}{\sqrt{2}} \frac{\alpha}{\sin^2 \theta_W \cdot M_W^2} = 1.1663 \times 10^{-5} \text{ GeV}^{-2} \ . \quad (3)$$

Substituting eq. (2) and the fine structure constant at the appropriate mass scale

$$\alpha(M_W^2) \simeq 1/128 \quad (4)$$

one gets

$$M_W \simeq 80 \text{ GeV}, \ M_Z = M_W/\cos\theta_W \simeq 91 \text{ GeV} \ . \quad (5)$$

The W and Z bosons were seen at these masses at the CERN $\bar{p}p$ collider and more recently at the Tevatron collider. Finally, it has been possible to produce millions of Z bosons and study its detailed properties at the large electron positron collider (LEP).

It would appear from the above discussion that all that remains to be seen at the future colliders is a definitive signal of the top quark! This is of course not the whole story, as we see below.

The Mass Problem (Higgs Mech.) – It arises from the fact that for massive vector bosons, the mass term in the Lagrangian breaks gauge invariance and hence the renormalisability of the theory. Let us consider the SU(2) gauge interaction, mediated by the Isotriplet of vector bosons

$$\vec{W}_\mu = W_\mu^{\pm,0},$$

in the presence of charged scalar particles represented by the complex field ϕ. We have

$$\mathcal{L} = \left(\partial_\mu \phi + ig\frac{\vec{\tau}}{2} \cdot \vec{W}_\mu \phi\right)^+ \left(\partial_\mu \phi + ig\frac{\vec{\tau}}{2} \cdot \vec{W}_\mu \phi\right)$$

$$-(\mu^2 \phi^+ \phi + \lambda(\phi^+\phi)^2) - \frac{1}{4} \ \vec{W}_{\mu\nu} \cdot \vec{W}_{\mu\nu},$$

$$\vec{W}_{\mu\nu} \equiv \partial_\mu \vec{W}_\nu - \partial_\nu \vec{W}_\mu - g\vec{W}_\mu \times \vec{W}_\nu \ . \quad (6)$$

The three terms in the Lagrangian from right to left represent the vector boson kinetic energy and self-interaction term, the scalar mass and self-interaction term and the scalar kinetic energy and gauge-interaction

term. Each of them is invariant under the gauge transformations

$$\phi \rightarrow e^{i\vec{\alpha}\cdot\frac{\vec{\tau}}{2}}\phi, \vec{W}_\mu \rightarrow \vec{W}_\mu - \frac{1}{g}\partial_\mu\vec{\alpha} - \vec{\alpha} \times \vec{W}_\mu \ . \tag{7}$$

But adding a mass term for the vector boson

$$M^2\vec{W}_\mu \cdot \vec{W}_\mu$$

will clearly break the gauge invariance.[2] In contrast, the scalar mass term is gauge invariant. This fact is used to give mass to the vector bosons through back-door. One starts with an Isodoublet of complex scalar field with imaginary mass,

$$\phi = \begin{pmatrix} \phi_3 & + & i\phi_4 \\ \phi_1 & + & i\phi_2 \end{pmatrix} \ , \quad \mu^2 < 0 \tag{8}$$

and turns on the Higgs mechanism [4]. Three of the scalar fields are absorbed as Goldstone bosons to give mass and hence longitudinal components to the 3 vector bosons, while the remaining one becomes a physical scalar particle (the famous Higgs particle) with real mass

$$M_{H^\circ} = M_W \left(\frac{2\sqrt{2\lambda}}{g}\right) \ . \tag{9}$$

Although the mass is related to the unknown scalar self-coupling λ, the validity of the perturbation theory implies

$$\lambda < 1 \Rightarrow M_{H^\circ} < 1 TeV \ . \tag{10}$$

Finally, the Higgs coupling to the vector bosons as well as the quarks and leptons (not mentioned so far) are predicted to be

$$g_{HWW,HZZ} = g \cdot M_{W,Z}$$
$$g_{Hq\bar{q},H\ell\bar{\ell}} = \tfrac{1}{2}g \cdot \frac{M_{\ell,q}}{M_W} \ . \tag{11}$$

Thus the Higgs particle has appreciable couplings only to the heavy particles like W, Z bosons or the t quark; and the best place to look for it is in the decay of Z or the toponium ($t\bar{t}$) state.[3] Even then the

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[2]All these are very similar to the QED case.

[3] Unfortunately the high top quark mass makes it too unstable to form toponium states.

branching ratio is tiny, so that one needs copious production of Z as provided by the LEP (e^+e^-) collider. It has yeilded a lower mass bound of about 60 GeV [1] for Higgs particle which is close to its discovery limit. The search can be pushed up further to about 80 GeV at LEP-II. If we do not find a Higgs particle in this mass range, then the search must be extended over the hundreds of GeV range since the theoretical mass limit is 1 TeV. This is the main physics goal of LHC, which is proposed to be a 14 TeV pp collider. The reason for the pp option instead of $\bar{p}p$ is its high luminosity and hence a higher mass reach for the Higgs search.

Hierarchy Problem (SUSY Soln.) – Solving the mass problem by the Higgs scalars leads to the so-called hierarchy problem. The property that scalar particle mass is not protected by any gauge symmetry, which was in fact used to solve the mass problem, implies that they are quadratically divergent under radiative correction (Fig. 2). Consequently the output Higgs mass would become as large as the cutoff scale of the electroweak theory, i.e.

$$M_H \rightarrow M_{GUT}(10^{16} \text{ GeV}) \text{ or } M_{\text{Planck}}(10^{19} \text{ GeV}).$$

How to restrict the Higgs mass to

$$M_H \sim M_W \sim 100 \text{ GeV}?$$

By far the most attractive solution to this problem is provided by supersymmetry (SUSY) [5]. It provides canceling contributions from radiative loops with Higgsino, fermionic superpartner of the Higgs scalar (Fig. 2). For the cancellation to be exact up to a mass scale of ~ 100 GeV, one requires

1) Exact supersymmetry in the couplings

2) A bound on supersymmetry breaking in masses

$$M_{\tilde{H}} - M_H = \Delta M \lesssim 100 \text{ GeV}.$$

Thus one expects to see superpartners of standard particles – scalar partners of quarks and leptons ($\tilde{q}, \tilde{\ell}$) and fermionic partners of gauge and Higgs bosons ($\tilde{g}, \tilde{\gamma}, \tilde{W}, \tilde{Z}, \tilde{H}$) – within the mass scale of several hundred GeV. Search for such particles is an important programme

of present and proposed colliders. By far the strongest mass bound on superparticles comes from the CDF experiment [6] at the Tevatron ($\bar{p}p$) collider, i.e.

$$M_{\tilde{q},\tilde{g}} > 140 \text{ GeV}. \tag{12}$$

The ongoing CDF and $D\oslash$ experiments at Tevatron are expected to extend this search up to a mass range of ~ 250 GeV. The search can be extended to over 1 TeV at LHC.

It is clear from the above discussions that the searches for top quark, Higgs boson(s) and possible superparticles are the most important physics objectives of the forthcoming high energy collider experiments. While it will take a 21st century machine like LHC to carry on the Higgs boson and superparticle searches upto their predicted mass bounds of ~ 1 TeV, there is a strong indirect evidence for the top quark to lie in the mass range of ~ 170 GeV. This comes from the radiative correction to eq. (3) coming from the $t\bar{b}$ loop contribution to W self energy (Fig. 3) and the analogous $t\bar{t}$ contribution to the Z self energy. Since these vector bosons acquire longitudinal components by swallowing Higgs scalars their fermionic couplings are propertional to the fermion mass (eq. 11), which can be sizeable for a large M_t. The resulting radiative correction is quadratic in M_t. More precisely eq. (3) has a radiative correction factor $(1 + \Delta r)$, where

$$\Delta r \simeq \frac{-3\sqrt{2}}{16\pi^2} G_F \; \cot^2\theta_W M_t^2 \tag{13}$$

for $M_t \gg M_W$. Thus for $M_t \geq 200$ GeV, one would get untenably low values of $\sin^2\theta_W$ or M_W (M_Z). Consistency with the precission measurements of these quantities (particularly at LEP) requires [1]

$$M_t \simeq 170 \pm 25 \text{ GeV}. \tag{14}$$

Therefore one expects a definitive top quark signal to emerge from the ongoing experiments at the Tevatron $\bar{p}p$ collider.

Top Quark Search – The hadron colliders are the most promising machines for top quark search because of their high energy reach. But the signal is messy; and one has to use special tricks to separate it from the background. The dominant mechanism for top quark production

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is the so-called flavour creation process via gluon-gluon fusion (Fig. 4) and quark-antiquark fusion (Fig. 1a), i.e.

$$gg(\bar{q}q) \to \bar{t}t. \tag{15}$$

One looks for a prompt charged lepton ℓ (i.e. e or μ) coming from its leptonic decay

$$t \to b\nu\ell \tag{16}$$

which eliminates the background from gluon and ordinary stable quarks (u, d, s). Of course the charged lepton could come from the unstable quarks b and c, i.e.

$$gg(\bar{q}q) \quad \to \quad \bar{b}b, \bar{c}c;$$
$$b \to c\nu\ell, \quad c \quad \to \quad s\nu\ell. \tag{17}$$

These background can be effectively suppressed by requiring the charged lepton to be isolated from the other particles. Because of the large energy release in the decay of the massive top quark, the decay products come wide apart. In contrast the energy release in the light b or c quark decay is small, so that the decay products come together in a narrow cone – i.e. the charged lepton appears as a part of the decay quark jet. The isolated lepton signature provides a simple but very powerful signature for top quark, first suggested in [7]. Using this signature the top quark search was carried out at the CERN $\bar{p}p$ collider and then at the Tevatron collider – the latter giving a mass limit of $M_t > 89$ GeV [8].

With the luminosity upgrade of the Tevatron collider it is possible now to extend the search to the mass range of $100 - 200$ GeV. A top quark in this mass range decays into a real W boson, so that one has a $2W$ final state, i.e.

$$\bar{t}t \to \bar{b}bWW \to \bar{b}b\bar{q}q\ell\nu. \tag{18}$$

The most serious background in this case is direct W production with additional QCD jets,

$$\bar{q}q \to ggW \to j_1 j_2 \ell\nu. \tag{19}$$

Since the QCD jets are largely soft and/or collinear, they can be suppressed to a large extent by transverse momentum and invariant mass

cuts – e.g. $p_j^T > 60$ GeV, $M_{j_1j_2} \sim 80$ GeV – without affecting the signal. Fig. 5 shows an early prediction of the $\bar{t}t$ signal and the $W + 2$ jets background with these cuts for the Tevatron upgrade [9]; the right hand scale corresponds to a luminosity of 100 pb^{-1}. One sees firstly that for the relatively clean dilepton channel, corresponding to leptonic decay of both the W bosons in (18), one has a measurable signal upto $M_t \sim 150$ GeV. For the isolated lepton plus multijet channel the signal remains measurable right upto $M_t \sim 200$ GeV, although one has to contend with a formidable background. Here one hopes to be helped by the fact the signal is dominated by 3 jets accompanying the isolated lepton, for which the QCD background would be further suppressed by an order of magnitude [9,10]. Finally the presence of a pair of b quark jets in the signal (18) would help to enhance the signal to background ratio further, if one has a reasonably efficient b identification.

Recently the CDF collaboration from Tevatron has reported [2] the observation of 26 events in the W ($\to \ell\nu$) $+ 3$ or more jets channel against the expected background of ~ 13 events from $W+$ QCD jets. The excess is consistent with a top quark signal of mass ~ 175 GeV (Fig. 6). They also have a reasonable efficiency of b identification ($\sim 30\%$) by combining informations on its decay vertex in the microvertex detector and on the lepton coming from its semileptonic decay. Requiring at least one identified b jet leaves a sample 7 events against an expected background of 1.4 (Fig. 7). The excess of 5.6 events has been tentatively interpreted as a top quark signal of mass ~ 175 GeV [2]. But of course the data sample is too small to draw any definitive conclusion. It may be noted here that this data sample was based on a luminosity of ~ 20 pb^{-1}, while the ongoing CDF and $D\oslash$ runs at the Tevatron are expected to accumulate a luminosity of ~ 100 pb^{-1}. Therefore a more definitive picture is expected to emerge soon. Even then one would have of course no more than a dozen or two of top candidate events. With an accumulated luminosity of ~ 1000 pb^{-1}, expected for the next phase of the Tevatron upgrade, one expects to see ~ 100 top quark events. This will be sufficient to establish a definitive top signal, but still inadequate to study its decay properties.

In contrast one expects copious production of top at the LHC. In the cleanest ($e\mu$) channel, shown in Fig. 8 [11], one expects a top cross-section of $\sim 10^4$ fb. This corresponds to a cross-section of $\sim 10^5$ fb in the lepton + multijet channel (18) discussed above. Even with the

low luminosity option of LHC (~ 10 fb^{-1}/year), this would imply an annual rate of ~ 1 million top quark events – i.e. similar to the rate of Z events at LEP. This will enable one to study its decay properties in detail and in particular to search for new particles in the decay of top. In particular there is a good deal of recent interest in the search of one such new particle in top quark decay, i.e. the charged Higgs boson $H^{\pm}$ of the supersymmetric standard model. This will be our next topic of discussion.[4]

Charged Higgs Boson Search – The minimal supersymmetric standard model (MSSM) has two Higgs isospin doublets with opposite hyper-charge $Y = \pm 1$ to ensure anomaly cancellation between their fermionic partners [4,5]. The two doublets of complex scalar fields correspond to 8 independent scalars, 3 of which are absorbed as Goldstone bosons to give mass to the $W^{\pm}$ and Z. So there are 5 physical Higgs bosons – 3 neutral (h^0, H^0, A^0) and 2 charged ones ($H^{\pm}$). We have the following fermionic couplings of the charged Higgs boson in the diagonal KM matrix approximation,

$$\mathcal{L} = \frac{g}{\sqrt{2M_W}} H^+ \Big[\cot\beta M_t \bar{t}b_L \quad + \quad \tan\beta M_b \bar{t}b_R + \cot\beta M_c \bar{c}s_L$$

$$+ \quad \tan\beta M_\tau \bar{\nu}\tau_R \Big] + hc, \qquad (20)$$

where we have neglected the couplings propertional to the light quark and lepton masses. The subscript $L(R)$ stands for the left (right) handed spinor state and $\tan\beta$ represents the ratio of the two Higgs vacuum expectation values. In the supergravity models $1 < \tan\beta < M_t/M_b$.

As we see from (20), the t couplings to bH^+ and bW^+ are compa-rable over a large range of $\tan\beta$ and so are the H^+ couplings to $c\bar{s}$ and $\nu\tau^+$. Thus for $M_H < M_t$, one expects significant branching fractions for the decays

$$t \to bH^+$$
$$H^+ \to \tau^+\nu. \qquad (21)$$

In contrast to the preferencial H^+ decay into τ, there is a universal branching fraction ($= 1/9$) for W boson decay into the 3 lepton species,

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[4]We shall not discuss neutral Higgs boson search further since it is covered in the talk of R.J.N. Phillips [12].

i.e.

$$t \to bW^+$$
$$W^+ \to e^+\nu, \mu^+\nu, \tau^+\nu. \tag{22}$$

Thus an excess of top decay into τ vis a vis the e, μ channels

$$B_{t \to b\tau\nu} > B_{t \to be\nu, b\mu\nu} \tag{23}$$

constitutes a distinctive signature for charged Higgs boson [13].

A second signature for charged Higgs boson is provided by the τ polarisation – the τ leptons coming from the decay of a scalar ($H^\pm$) and vector ($W^\pm$) boson have exactly opposite polarisations [14]. Using the two signatures one can carry on the $H^\pm$ search close to the top quark mass at LHC over the whole range of $\tan\beta$ [15].

For $M_H > M_t$ one still expects a sizeable rate of $H^\pm$ production at LHC via the gluon $-b$ quark fusion

$$gb \to tH^- \to t\bar{t}b; \tag{24}$$

but the dominant decay mode into $\bar{t}b$ has an enormous QCD background. With a good b quark identification, however, one expects to have a viable signal if $\tan\beta \sim 1$ or very large ($\sim M_t/M_b$) [16,17]. Fig. 9 shows the expected signal against the QCD background for $\tan\beta = 1$ and 50 assuming a b-identification efficiency of 30% [16]. Interestingly, these two regions of $\tan\beta$ are theoretically favoured from the consideration of unification of Yukawa couplings at the GUT scale [18]. The underlying reason for favouring these two regions of $\tan\beta$ is of course the same in both the cases – i.e. a large $Ht\bar{b}$ Yukawa coupling a la eq. (20).

<u>Search for Superparticles</u> – Let me start with a brief discussion of R-parity, which underlies the canonical missing-p_T signature for super-particle search. The presence of scalar quarks and leptons ($\tilde{q}, \tilde{\ell}$) in SUSY imply baryon and lepton number violating interactions shown in Fig. 10. Moreover this diagram would imply proton decay with a typical time scale of weak interaction ($\tau_p \sim 10^{-8}$ sec!), since the mass of the exchanged particle $M_{\tilde{q}}$ is comparable to M_W. To forbid this catastrophic proton decay one assumes R-parity conservation, where

$$R = (-1)^{3B+L+2S} \tag{25}$$

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so that it is $+1$ for all the standard particles and -1 for their superpartners differing by half a unit of spin(S). It automatically forbids single emission/absorption of a superparticle. It implies that (i) the superparticles are produced in pair; and (ii) the lightest superparticle (LSP) resulting from their decay is stable. The LSP is also expected to be colour and charge neutral for cosmological reasons; and in most SUSY models it turns out to be the photino $\tilde{\gamma}$. Finally the LSP is expected to interact very weakly with matter like the neutrino (Fig. 11); and hence escape the detector without a trace. The apparent imbalance of transverse momentum (missing-p_T) resulting from this serves as a signature for superparticle production.[5]

The superparticles having the largest production rates at the hadron colliders are the strongly interacting ones, i.e. squark $\tilde{q}$ and gluino $\tilde{g}$. They are produced via gluon-gluon fusion (Fig. 12)

$$gg \rightarrow \tilde{g}\tilde{g} \text{ or } \tilde{q}\bar{\tilde{q}} \qquad (26)$$

and decay via

$$\tilde{q} \rightarrow q\tilde{\gamma}, \ \tilde{g} \rightarrow q\bar{q}\tilde{\gamma}. \qquad (27)$$

The decay of one of the squarks (gluinos) into a leading photino carrying the bulk of its momentum results in a large missing-p_T event accompanied by one or more jets. This is illustrated in Fig. 13; the number of visible jets depend on the jet detection algorithm. The rate of such large missing-p_T events can be predicted as a function of $\tilde{q}$ or $\tilde{g}$ mass by convoluting their pair production cross-section with the probability of one of them decaying into a leading $\tilde{\gamma}$ [19].

The SM background for large missing-p_T events come from prompt neutrino production processes, notably $W \rightarrow \tau\nu$ ($Z \rightarrow \nu\bar{\nu}$) accompanied by QCD jets. The size of this background can be estimated from the observed rate of $W \rightarrow \ell\nu$ ($Z \rightarrow \ell\bar{\ell}$) accompanied by QCD jets. Observation of no clear excess over this background has led to lower mass limits of $\tilde{q}$ and $\tilde{g}$ from the CERN $\bar{p}p$ and Tevatron colliders. The strongest mass limit of (12) is based on the early Tevatron data with an integrated luminosity of ~ 4 pb^{-1} [6]. With luminosity upgradation it is possible to extend to search to ~ 250 GeV. Finally the search can be carried up to the theoretical mass bound of ~ 1 TeV at the LHC.

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[5]Momentum balancing in the longitudinal direction is not possible in a hadron collider due to the loss of particles along the beam pipe.

Fig. 14 shows the expected gluino signal against the SM background at LHC [20].

There is a good deal of recent interest in a second type of superparticle signature – i.e. the multilepton and in particular the like sign dilepton signature. It arises from i) the leptonic decay of LSP in the R-parity violating SUSY model and ii) from the cascade decay of $\tilde{g}$ or $\tilde{q}$ into LSP ($\tilde{\gamma}$) via $\tilde{W}/\tilde{Z}$, which holds for the R-conserving SUSY model as well.

i) It is clear from Fig. 10 that proton stability requires B or L conservation, but not necessarily both. Hence one can have two types of R-violating SUSY models, corresponding to B and L violation [20]. The former implies LSP decay into a multiquark channel which are hard to distinguish from the QCD background; but the latter implies a distinctive leptonic decay of LSP

$$\tilde{\gamma} \rightarrow \ell \bar{q} q' \text{ (or } \ell \bar{\ell}' \nu). \tag{28}$$

Eqs. 26-28 imply at least 2 leptons in the final state; and they are expected to have like sign half the time, thanks to the Majorana nature of $\tilde{\gamma}$. This results in a distinctive like sign dilepton (LSD) signature for superparticle production in the R-violating SUSY model, analogous to the missing-p_T signature for the R-conserving model. The CDF dilepton data from the Tevatron collider [8] has been analysed in [21] to give a mass limit of

$$M_{\tilde{q},\tilde{g}} > 100 \text{ GeV} \tag{29}$$

in the R-violating SUSY model. This is comparable to the corresponding mass limit (12) for the R-conserving model. Using the LSD signature one can extend the $\tilde{g}$ search in the R-violating SUSY model upto a mass range of ~ 1 TeV at the LHC [22]. Moreover the LSD signature is also relevant for $\tilde{g}$ search at LHC in the R-conserving SUSY model as we see below.

ii) In the mass range of a few hundred GeV, the gluino undergoes cascade decay into photino via $\tilde{W}$ and $\tilde{Z}$. In particular

$$\tilde{g} \xrightarrow{50\%} \bar{q} q' \tilde{W} \tag{30}$$

followed by

$$\tilde{W} \rightarrow W \tilde{\gamma} \xrightarrow{20\%} \ell \nu \tilde{\gamma}. \tag{31}$$

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This means a leptonic branching fraction of $\sim 10\%$ for $\tilde{g}$ decay, i.e. a branching fraction of $\sim 1\%$ for a dilepton final state resulting from the $\tilde{g}\tilde{g}$ pair. Finally the Majorana nature of $\tilde{g}$ implies a LSD final state half the time. Despite its small branching fraction ($\sim 1/2\%$) the LSD channel provides a viable gluino signature upto $M_{\tilde{g}} \sim 1$ TeV at LHC because of the small SM background. Fig. 15 shows the expected gluino signal along with the background in the LSD channel as functions of the accompanying missing-p_T [22]. It may be mentioned here that the neutral and charged gauginos ($\tilde{\gamma}, \tilde{Z}$ and $\tilde{W}$) mix with their Higgsino counterparts; and one has to diagonalise the resulting neutralino and chargino mass matrices for a quantitative estimate of the gluino signal [22]. Nonetheless the simplified description of the signal outlined above is valid to a good accuracy.

Conclusion – In summary, the searches for top quark, Higgs boson(s) and possible superparticles are the three main physics objectives of Tevatron and the LHC. There is good reason to expect a definitive top quark signal in the mass range of ~ 175 GeV to emerge from the forthcoming Tevatron data. But one needs the LHC to carry the Higgs and superparticle searches over the predicted mass range going upto ~ 1 TeV. It should be noted here that the Higgs and supersymmetric particles are the minimal set of missing pieces which will complete the picture of elementary particles and their interactions. But of course this is not the only set. It may very well be that the nature has chosen an alternative way of completing this picture with a different (and larger) set of missing pieces. In that case one expects to see experimental signals of this new physics alternative in lieu of the Higgs and superparticles, but still in the energy range of $\lesssim 1$ TeV. Thus one hopes that the LHC data will help to complete the picture of elementary particle physics along the lines outlined above (i.e. the MSSM), or else provide crucial experimental clue pointing to the alternative route.

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Fig. 1. The basic amplitudes of (a) strong, (b) electromagnetic and (c) charged current weak interaction.

Fig. 2. The quadratically divergent contributions to the Higgs mass from the radiative Higgs loops (1,2) and the cancelling SUSY contribution from the Higgsino loops (3,4).

Fig. 3. Radiative correction to the W boson mass arising from the $t\bar{b}$ loop.

Fig. 4. Top quark production in $\bar{p}p$ (pp) collision via gluon-gluon fusion.

Fig. 5. Top quark contribution to the isolated lepton plus n-jet events and also dilepton events (dotted line) shown for the typical energy (2 TeV) and luminosity (100 pb^{-1}) of the Tevatron upgrade. The background to the 2-jet events from W plus 2-jet and W pair production processes are also shown. [9]

Fig. 6. Top mass distribution for 26 events in the $W + 3$ or more jet sample (solid histogram) and the background of 13 events (dots) obtained from $W+$ multijets Monte Carlo simulation. The dashed histogram represnts the sum of 13 $t\bar{t}$ Monte Carlo events with $M_t = 175$ GeV plus the 13 background events. [2]

Fig. 7. Top mass distribution for the data (solid histogram) and the background of 1.4 $W+$ multijets Monte Carlo events (dots) having a tagged b. The dashed histogram represents the sum of 5.6 $t\bar{t}$ Monte Carlo events with $M_t = 175$ GeV plus the 1.4 background events. [2]

Fig. 8. The expected $t\bar{t}$ signal at LHC in the cleanest ($e\mu$) channel shown against the p_T of the 2nd (softer) lepton. The $b\bar{b}$ background with and without the isolation cut are also shown. [11]

Fig. 9. The expected charged Higgs signals at LHS shown against the reconstructed $H^{\pm}$ mass along with the background. The cases $M_{H^{\pm}} = 200, 300, 400, 500$ GeV are shown for (a) $\tan\beta = 1$ and (b) $\tan\beta = 50$. [16]

Fig. 10. The proton decay process arising from squark exchange.

Fig. 11. Comparison of the rates of LSP ($\tilde{\gamma}$) and ν interaction with ordinary matter (e, q).

Fig. 12. Event configuration in the transverse plane for a pair of (a) squark and (b) gluino production at a hadron collider.

Fig. 13. Pair production of (a) gluino and (b) squark via gluon-gluon fusion.

Fig. 14. ISA JET Monte Carlo prediction for missing $-E_T$ distribution after selection cuts for (a) $M_{\tilde{g}} = 300$ GeV and (b) $m_{\tilde{g}} = 100$ GeV at LHC. The solid (dashed) line corresponds to the gluino signal for $\tan\beta = 2(10)$, while the points represent the total SM background. [20]

Fig. 15. The expected LSD signals for different gluino masses (300,600,1000 GeV) shown against the accompanying missing-p_T along with the dominant background (dashed line) at LHC. The signal curves are for the R-conserving SUSY model with $\tan\beta = 2$ and the Higgsino mass parameter $\mu = 4M_W$. [22]

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